Natural Gas Engine and Vehicle Research, Development and Demonstration

Engine Development

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NREL Natural Gas Engine and Vehicle Research, Development and Demonstration

(NG RD&D) Program Task A

Southwest Research Institute

National Renewable Energy Laboratory

California Energy Commission

South Coast Air Quality Management District

Doosan Infracore

Woodward, Inc.

LA Metro

NREL Natural Gas Engine and Vehicle Research, Development and Demonstration

- **NREL Project Overview**
- Path from Lean to Stoich EGR
- Current Status
- Future

NREL Project Overview

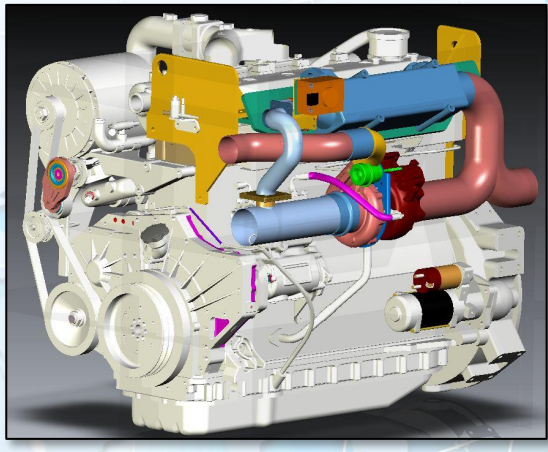
- **Project Objective**
  - **Develop dedicated natural gas engine for initial use in an articulated bus that produces near zero emissions without sacrificing performance or efficiency compared to 2010 diesel engine**
- **Project Goals**
  - **NOx: 0.05 g/hp-hr vs. 2010 0.2 g/hp-hr**
  - **PM: near zero**
  - **Performance/Efficiency: 2010 diesel equivalent**
  - **CO2: 15% reduction from current diesel options**
  - **Cost: less than 2010 diesel w/after-treatment**
  - **Secondary goal: NH_3< 10 ppm**

Project Overview

Production Lean Burn Engine

- **Production Engine Modifications**
  - Lean Burn to Stoichiometric operation
  - Cooled EGR
  - Advanced Ignition System
  - High efficiency turbo matching
  - Optimized Aftertreatment
  - Optimized in-cylinder turbulence
  - Optimized Piston Design
  - Optimized Camshaft Profile
- **Testing**
  - Thermal Analysis
  - Structural Analysis
  - Steady State and Transient Calibrations
  - Durability Testing
  - Certify to 2010 emission levels

Task A



Modified Engine

- **Engine Brought to Production Levels**
  - Collaboration with engine OEM and their suppliers
- **Engine Integrated into Chassis**
  - Collaboration with chassis OEM and their end users
  - Vehicle Emissions Measurements
  - Engine sensor data logging to compare to baseline vehicles

Tasks B and C

Chassis Integration

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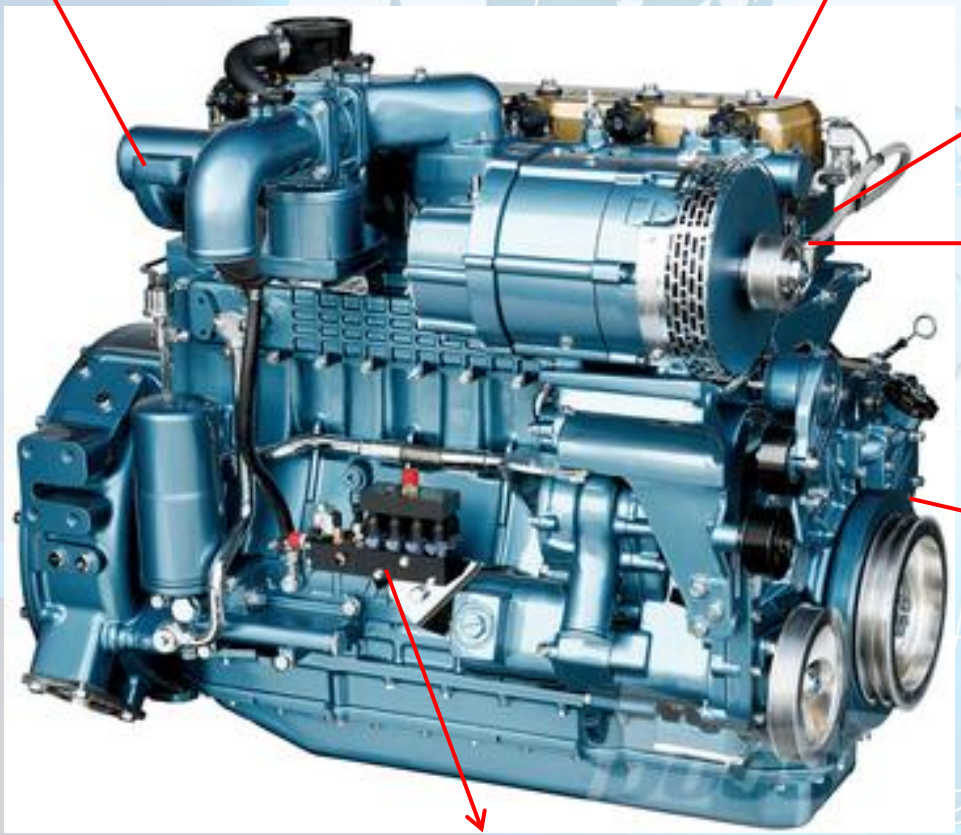
2010 Lean Burn Engine

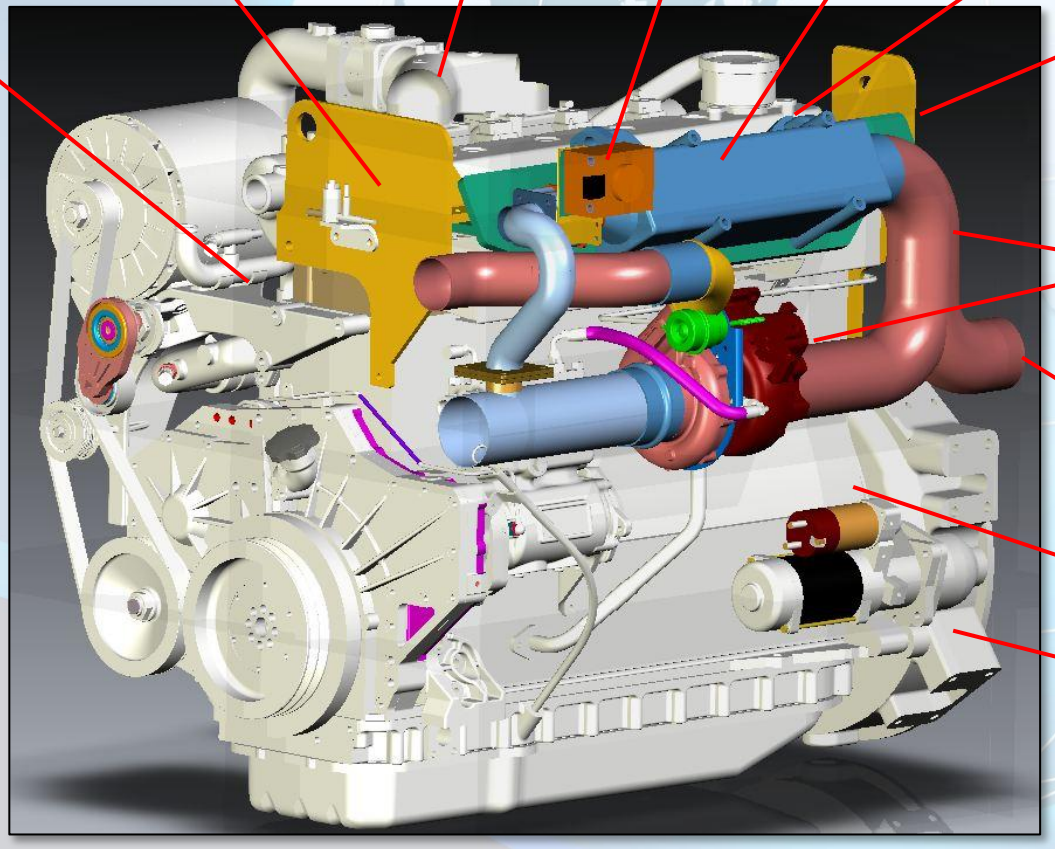
- Cert Data
  - NMHC = 0.08 g/bHp-hr
  - NO_x = 0.156 g/bHp-hr
  - CO = 0.08 g/bHp-hr
  - NH_3 < 10 ppm
- Power = 220kW
- Torque = 1220Nm
- Peak Efficiency ~ 40%



Stoich EGR Engine

11.5:1 compression ratio, high squish, gallery cooled Pistons

- Estimated Cert Level
  - NMHC = 0.08 g/bHp-hr
  - NO_x = 0.05 g/bHp-hr
  - CO = 0.1 g/bHp-hr
  - NH_3 < 10 ppm
  - CH_4 lower than lean burn
- Power = 250kW
- Torque = 1630Nm
- 18.5 bar BMEP
- Peak Efficiency = 41%

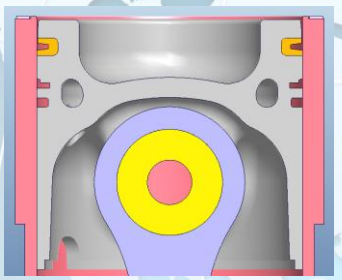


Ignition Selection

- **Stock Coils**
  - **30 mJ – Peak efficiency at 18% EGR**
  - **43 mJ – Higher peak efficiency at 25% EGR**
- **Dual Coil Offset (DCO)**
  - **5-Strike – More EGR tolerance, but no efficiency gain**

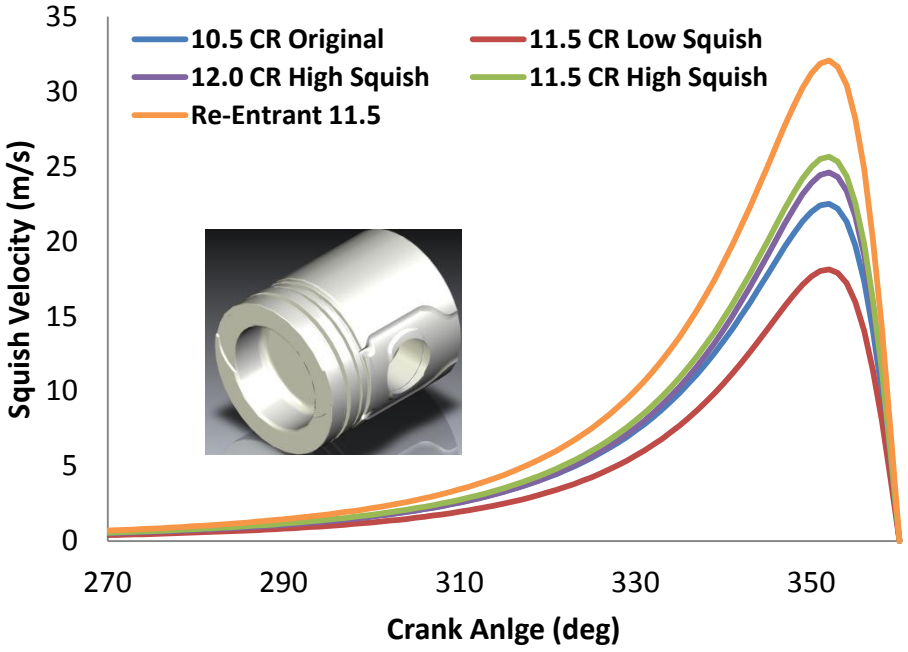
Piston Selection

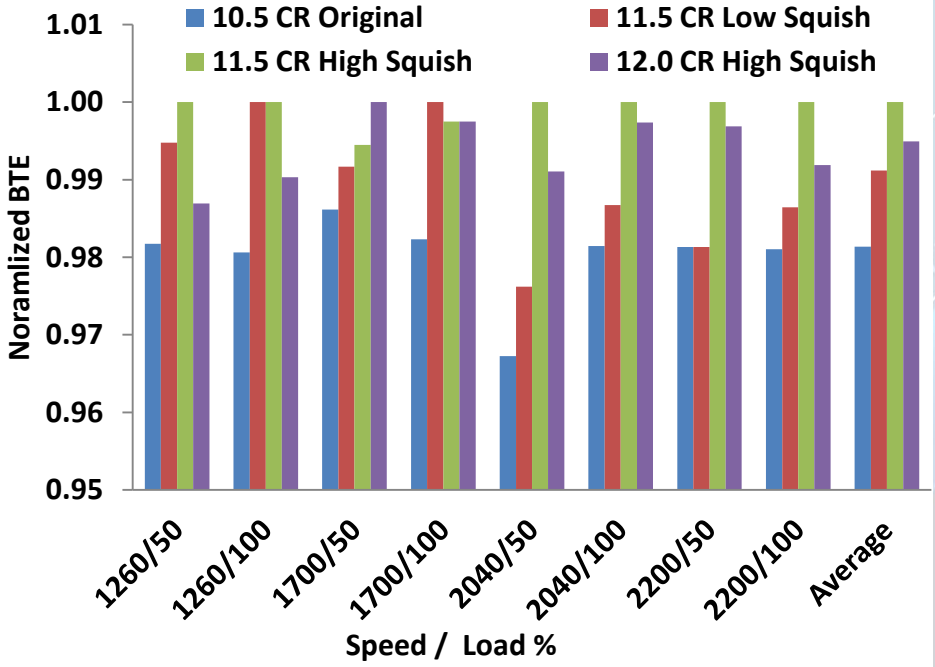
- **Piston consideration**
  - Reduce exhaust temperature
  - Improve thermal efficiency
  - Improve EGR tolerance



High Squish

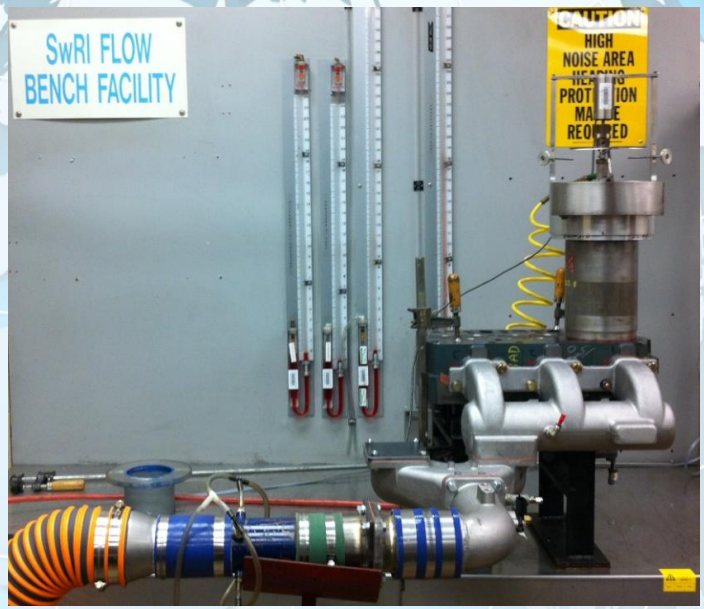
Re-entrant Bowl

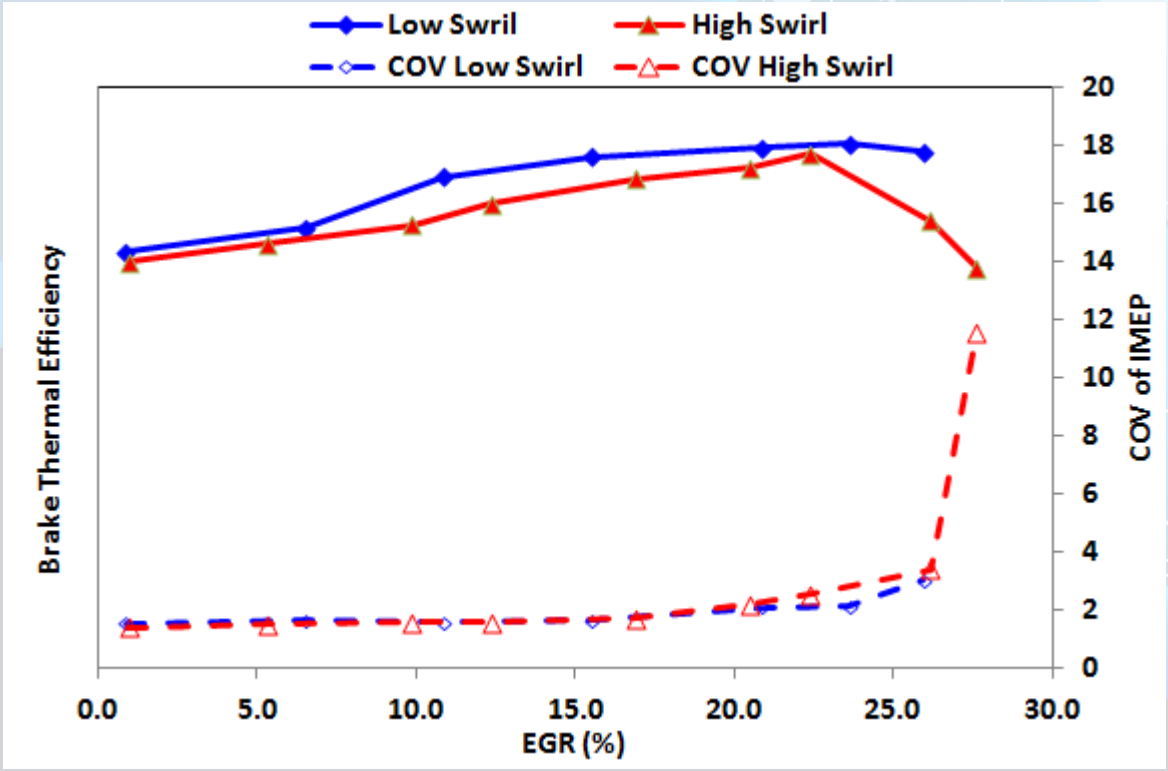


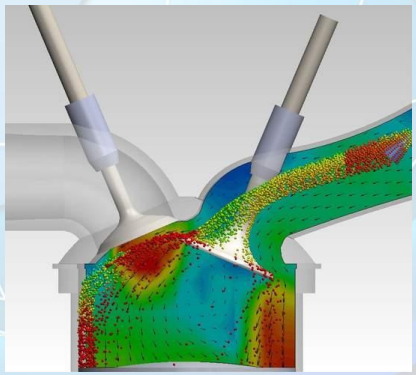


Head Selection

- High vs. low swirl
  - Tried to extend EGR tolerance with high swirl head
  - Low swirl head demonstrated similar EGR tolerance with higher volumetric efficiency

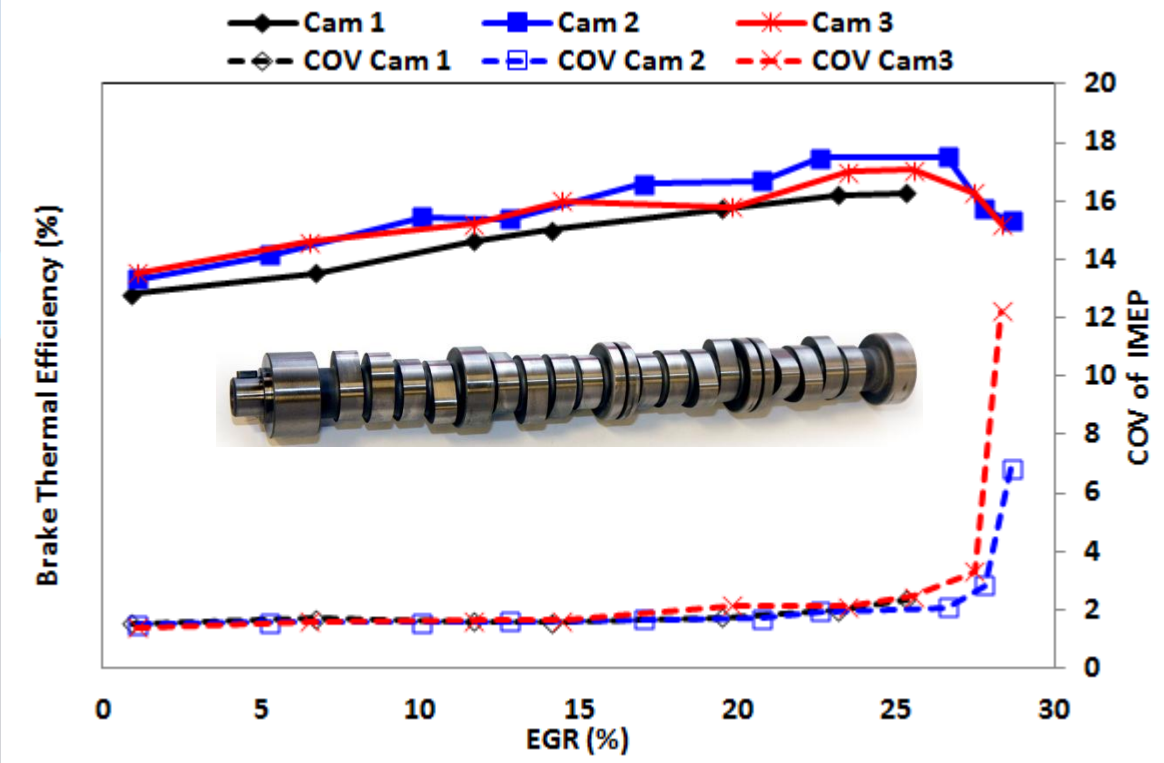


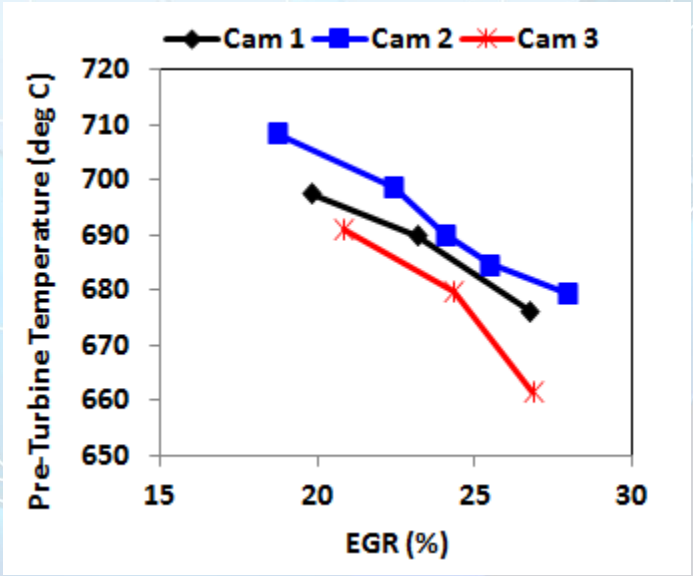




Cam Selection

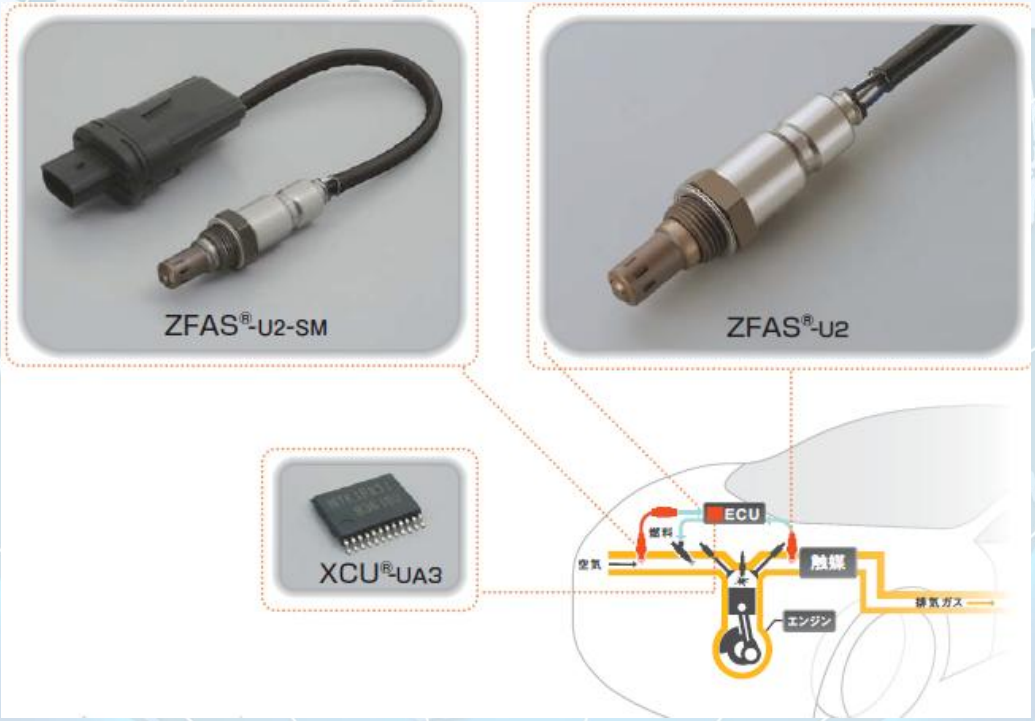
- Cam study
  - Reduced overlap from original diesel cam (Cam 2)
  - Retarded intake opening to reduce exhaust temperature (Cam 3)
  - Small change in efficiency
  - Improved material for durability





Intake UEGO Selection

- Intake UEGO for EGR measurement
  - Typical UEGO were designed for use in the exhaust
  - Issues with using these in the intake
- Intake Specific UEGO
  - NTK ZFAS – U2-SM
  - Designed for intake use
  - Currently running in our calibration durability engines



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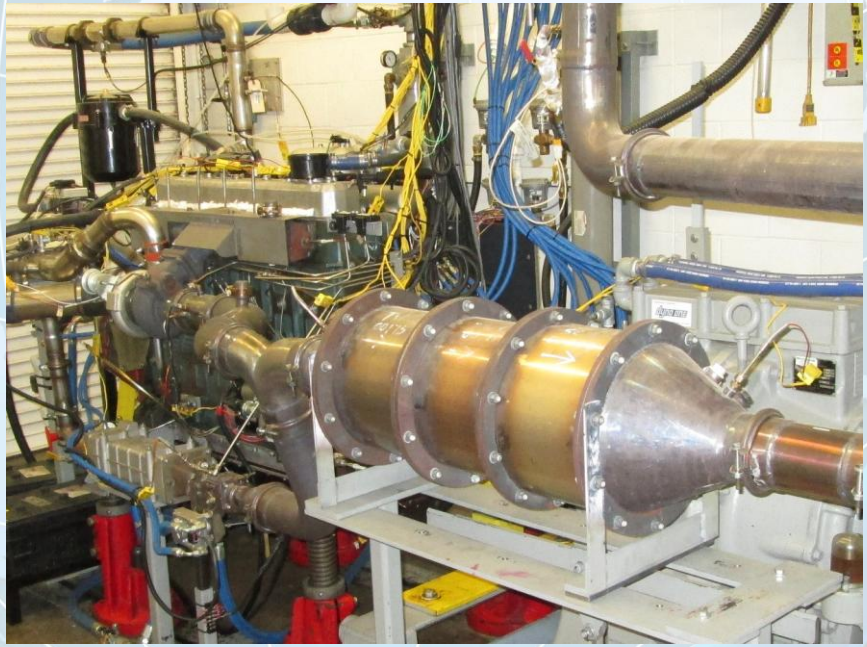
Current Status

- **Engine Calibration 90.37% complete**
  - One Engine
  - Working on safeties and engine protection
  - NO_x / NH_3 tradeoff
- **Durability testing started** (SwRI Facility)
  - Four engines
  - High coolant temperature test
  - Rated power
  - Thermal shock
  - Preliminary DF Testing
- **Certification**
  - Two engines
  - DF Testing
  - Certification Testing

Calibration / Development

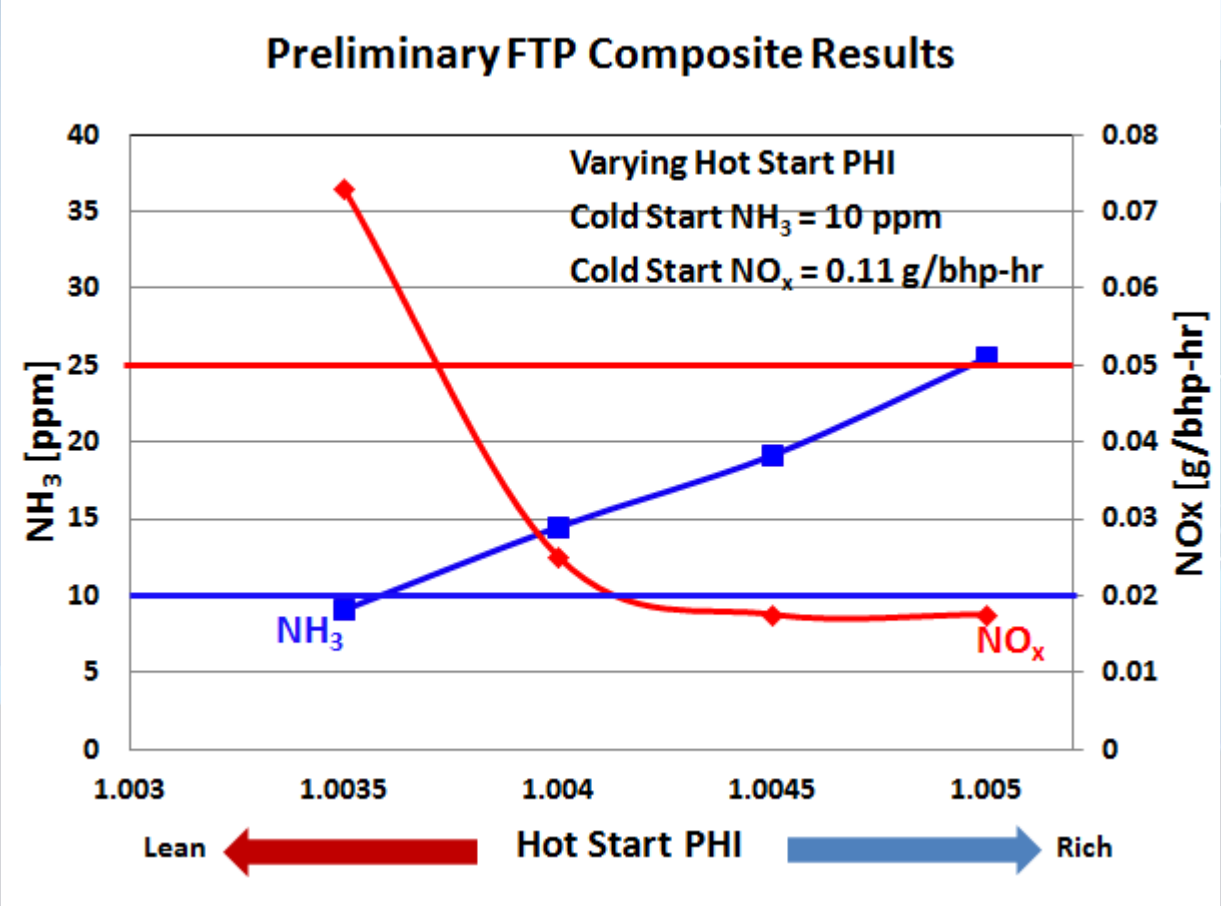
- **Calibration / Development work is almost complete**
  - **Almost all of the hardware configuration has been selected**
  - **Software is production ready**
  - **Calibration for normal operation is completed, able to run durability tests and even an FTP**
  - **Further calibrations needed for safety protection**
    - **Knock and misfire detection**
    - **Catalyst monitoring**
    - **Engine manufacturers diagnostics**



Calibration Engine

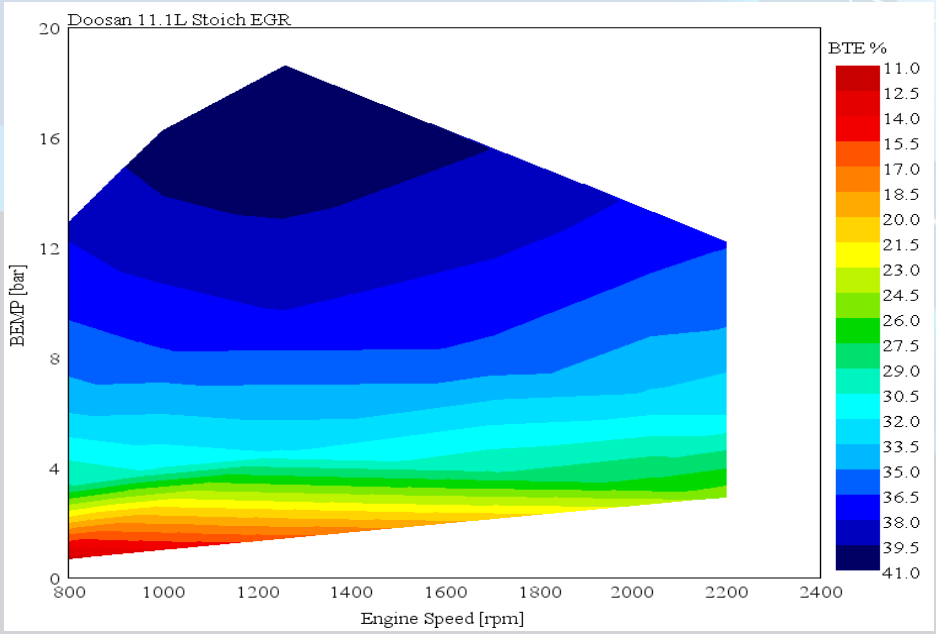
NOx / Ammonia Tradeoff

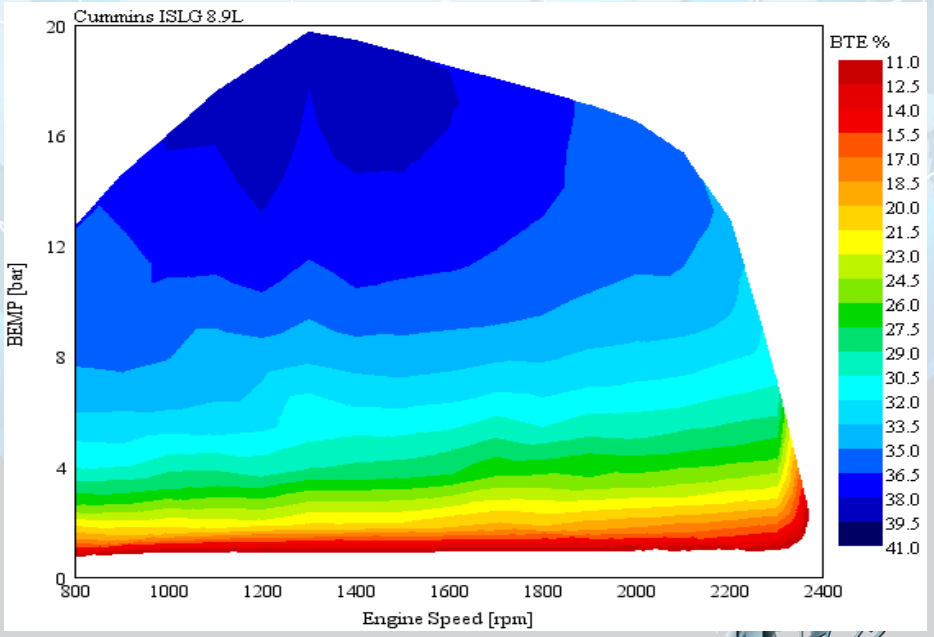
- Working on controls improvements
  - Lean / Rich excursions
- Investigating hardware changes
  - Multiport injection
- Investigating after-treatment
  - Passive SCR or AOC
- CARB project exploring these options on this engine
- 2014 NOx Regulation
  - CARB & EPA No Change from 2010
  - EURO6 = 0.46 g/kW-hr, 10 ppm NH3



Current Status of Efficiency

- Doosan 11.1L
  - Peak Power = 250 kW
  - Peak Torque = 1630 Nm
  - Peak BMEP = 18.6 bar
  - Peak Efficiency = 40.9%
  - NOx = 0.03 g/bhp-hr
  - CO = 2.2 g/bhp-hr
- Cummins Westport 8.9L
  - Peak Power = 239 kW
  - Peak Torque = 1356 Nm
  - Peak BMEP = 19.8 bar
  - Peak Efficiency = 38.7%
  - NOx = 0.13 bhp-hr
  - CO = 8.1 g/bhp-hr

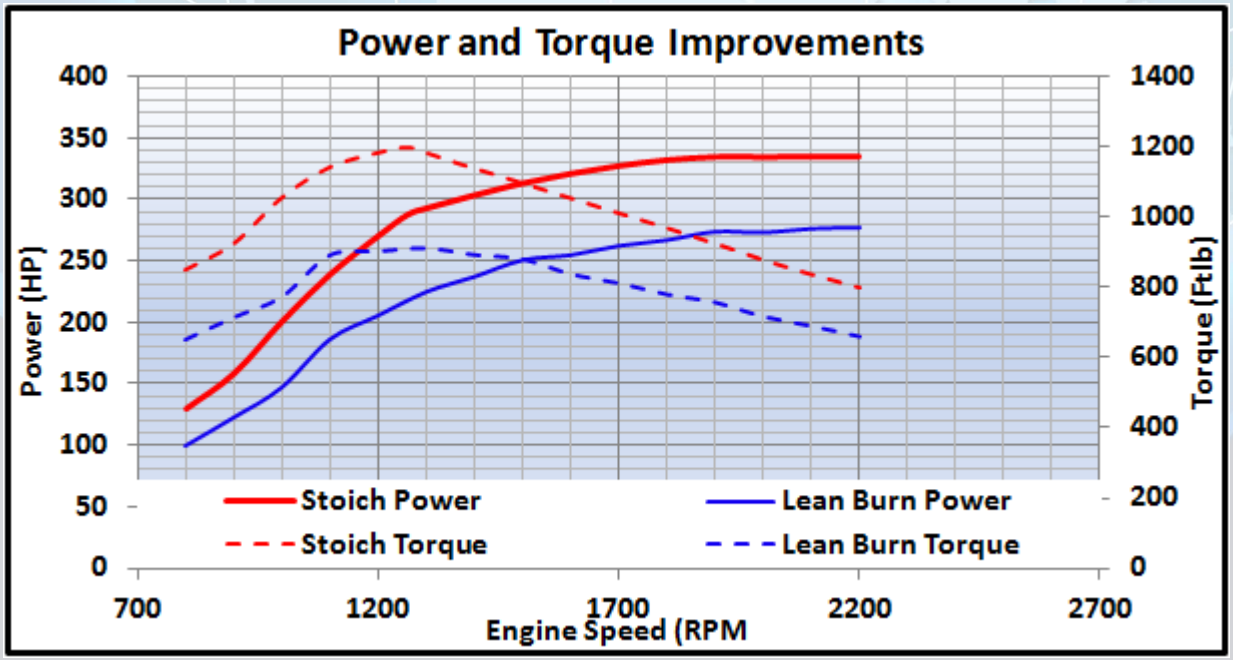




Lean to Stoich Summary

- Summary of Part Change
  - Higher energy Ignition
  - Increased squish / CR piston
  - Cam
  - Exhaust manifold material
  - Turbine housing material
  - EGR cooler and valve
  - Three-way Catalyst
  - Crank wheel for misfire
  - Knock Sensors
  - Retain LS Heads

- Challenges
  - Exhaust temperature
  - Piston temperature
  - Increased cooling requirements
  - EGR measurement
  - EGR water dropout \ corrosion



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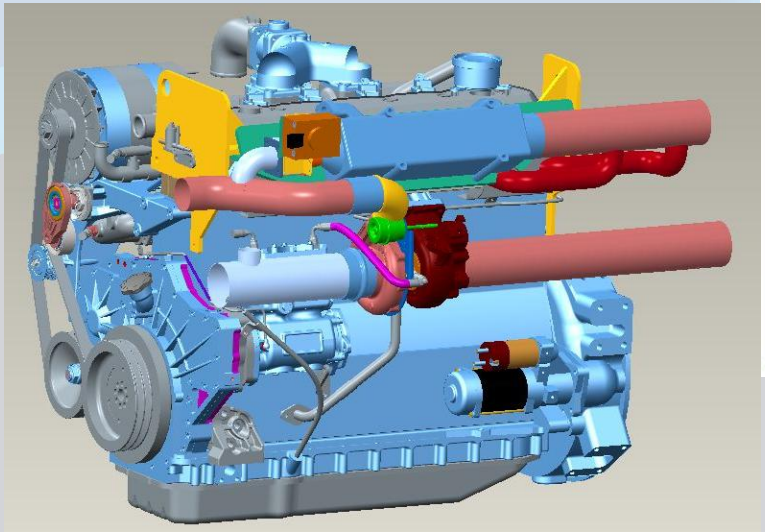
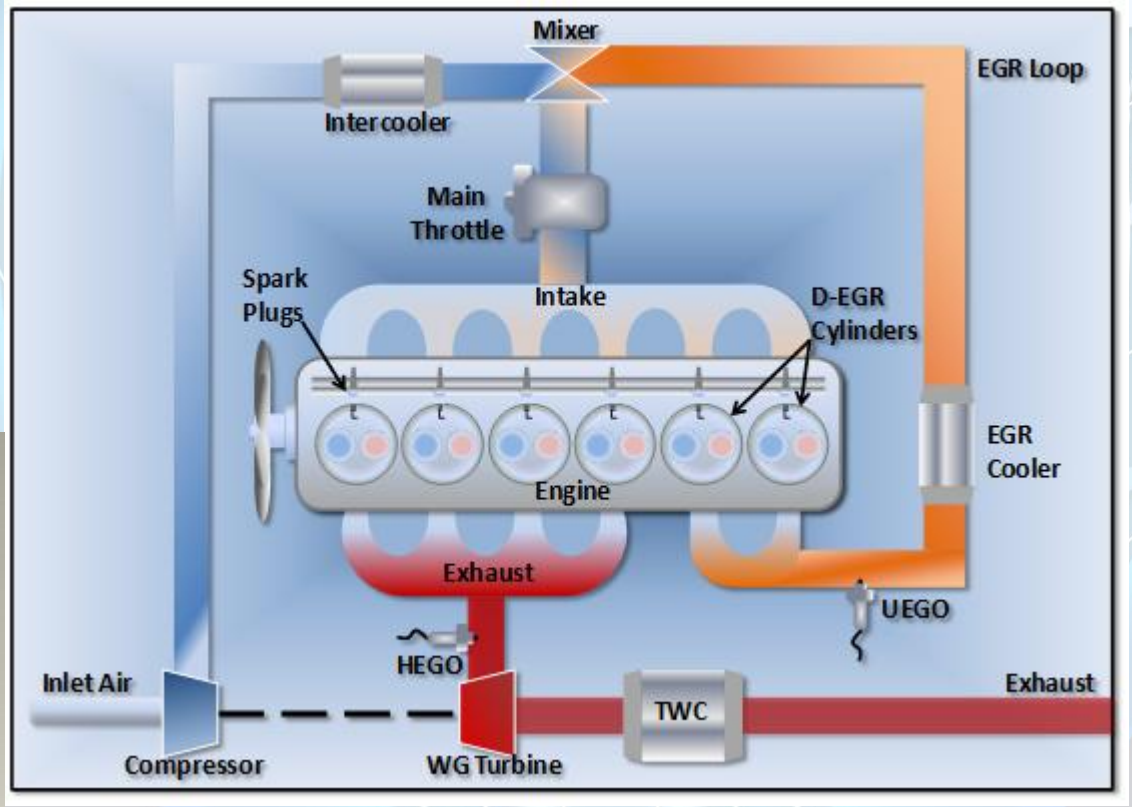
Future

- **Dedicated EGR**
  - **2 cylinders**
  - **Up to 33% EGR**
  - **BTE approaching 46%**
  - **NO_x = 0.02 g/bhp-hr**
  - **NH_3 < 10 ppm**





Thank You

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